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Durability of Quick Reaction Satellite Antenna (QRSA) Trunnion Castings

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Repeated failures of quick reaction satellite antenna (QRSA) trunnion castings in the field caused alarming concerns about their durability. Arguments over the cause of the failures, ranging from improper installation, unbalanced and/or excess force to poor design and insufficient material strength, have been disputed between the contractor and the government engineers. Incipient melting during solution treatment was also suspected as one of the reasons responsible for cracking in the original aluminum castings. This study compared the microstructures of as-cast and heat-treated samples and concluded that incipient melting did not occur during solution treatment and thus was not the principal cause for cracking in the aluminum castings. Eventually, the light aluminum alloy was replaced by a heavier but stronger ductile iron. As a result, the durability of the QRSA trunnion casting has been significantly improved and the deficiency was remedied.

14. SUBJECT TERMS
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HISTORICAL BACKGROUND

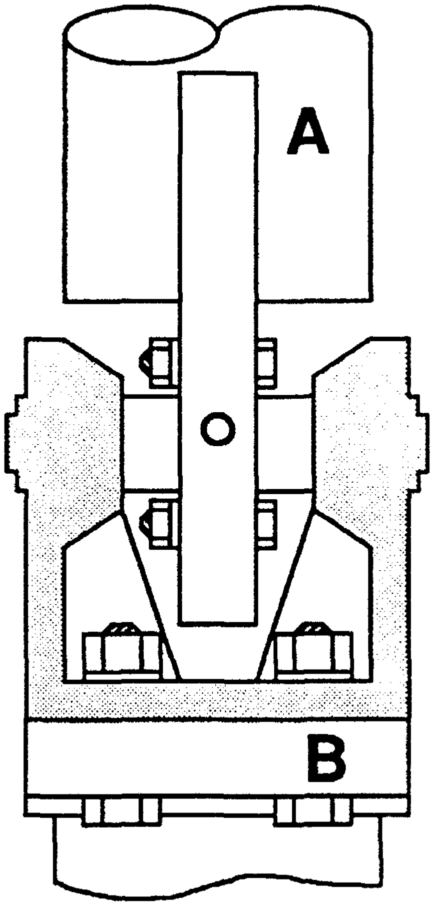
The quick reaction satellite antenna (QRSA) trunnion casting connects the antenna and the base as shown in Figure 1. It was originally a 771.0 aluminum alloy (Al-7Zn-0.9Mg) casting. The contractor, Harris Corporation, Melbourne, Florida, first reported defects in the Al QRSA trunnion casting on October 30, 1987. Material deficiency, improper heat treatment and irregularity of installation were cited as the major causes for these cracks. As a result, all fielded Al QRSA trunnion castings had to be replaced. Subsequently, the Government approved the implementation of an Engineering Change Proposal (ECP#62 - includes improved flatness tolerance) submitted by the contractor in April, 1988. Although the problem was considered solved, another failure of a modified Al QRSA trunnion casting (SN10A) was reported in early 1989 at Fort Bragg. The improper implementation of the engineering change by the contractor was cited as the cause. Cracks were later found in trunnion castings at Shaw Air Force Base (AFB); these were sent to the Naval Aviation Depot, Materials Engineering Laboratory (NMEL), Jacksonville, Florida for analysis. These cracks were partially attributed to stresses set up by surface mismatch between the trunnion casting and the pallet. The Naval Aviation Laboratory performed a finite element analysis that suggested an inadequate trunnion design and also experimentally found a latent flaw in the sample part; NMEL concluded that the casting might have been overheated during solution treatment causing incipient melting. In July, 1990, another crack in a trunnion casting (SN004A) was found at Patrick AFB. These repeated failures and continuous disputes over the causes of these failures have irritated both the Government and the contractor. A potential for legal action was emerging. To look for a second opinion and best protect the Government's interests, three Al QRSA trunnion castings were sent by Communication Electronics Command, Center for Space Systems (CECOM), Fort Monmouth, New Jersey, to the U.S. Army Research Laboratory (formerly the U.S. Army Materials Technology Laboratory), Watertown, Massachusetts for evaluation in October, 1990.

EVALUATION PROCEDURES

Cracks were hardly visible with the naked eye on the three Al QRSA trunnion castings first received at the U.S. Army Research Laboratory-Watertown (ARL-Watertown) because of the external paint. For a better surface examination one Al casting was sent to CDS Group, Houston, Texas, for paint stripping. The painted and stripped sample trunnion castings are shown in Figure 2. Figures 2a and b reveal the overall view of the Al trunnion casting, while Figure 2c shows the bottom view of the stripped part, and Figure 2d reveals cracks adjacent to the bolt hole "x" at higher magnification.

To determine the heat treatment effect, one as-cast 771.2 aluminum alloy ingot was obtained from the contractor for microstructural examination and comparison. During the course of this evaluation, the contractor had decided, with Government approval, to change the cast material from 771.0-T6 aluminum alloy to ductile iron (grade 100-70-03). ARL-Watertown was also furnished with one sample of this ferrous casting. In this study, the following evaluation procedures were followed:

- Part and Material Identification
- Paint Removal
- Microstructural Analysis
    - Metallographic Examination
    - SEM Fractographic Study
- Radiographic Analysis



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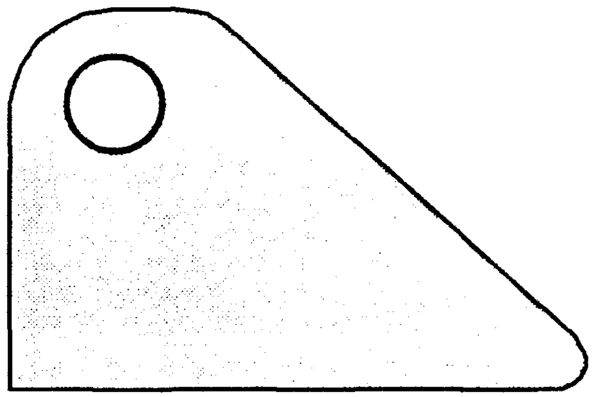

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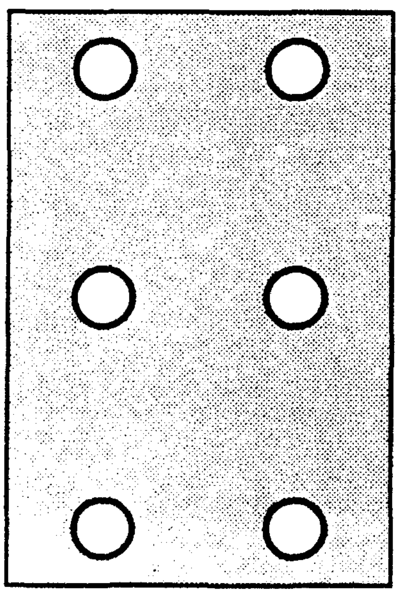


(c)

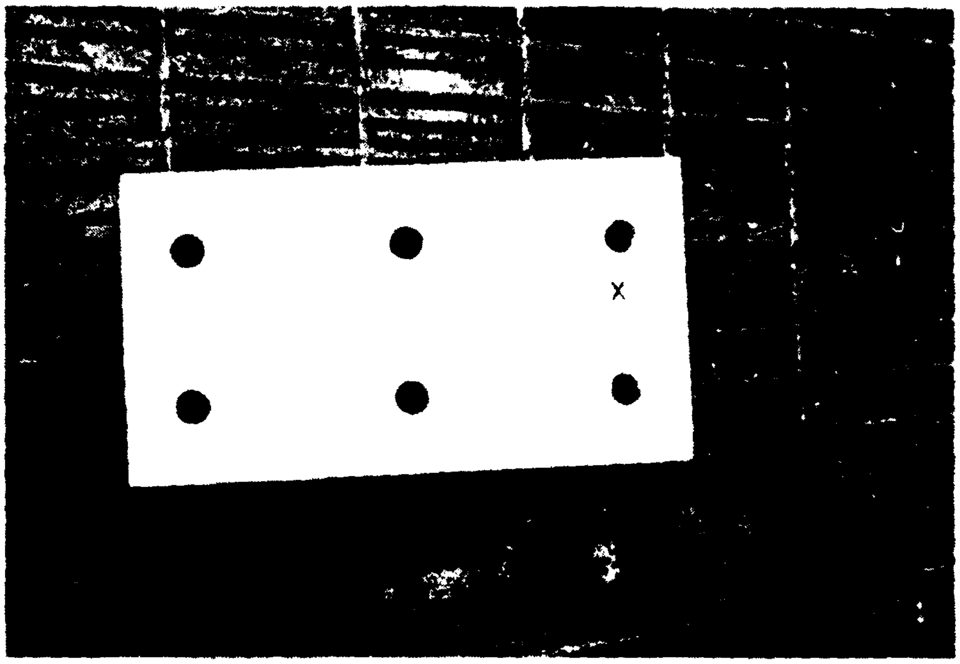
Figure 1. The quick reaction satellite antenna trunnion casting (shaded) showing (a) the overall view of the connection between the antenna (A) and the base (B), (b) side view and (c) bottom view.

Figure 2. Painted and stripped Al trunnion castings: (a) and (b) overall views,

(a)

(b)

Figure 2. Painted and stripped Al trunnion castings: (c) bottom view and (d) hair-line cracks adjacent to the bolt hole x.



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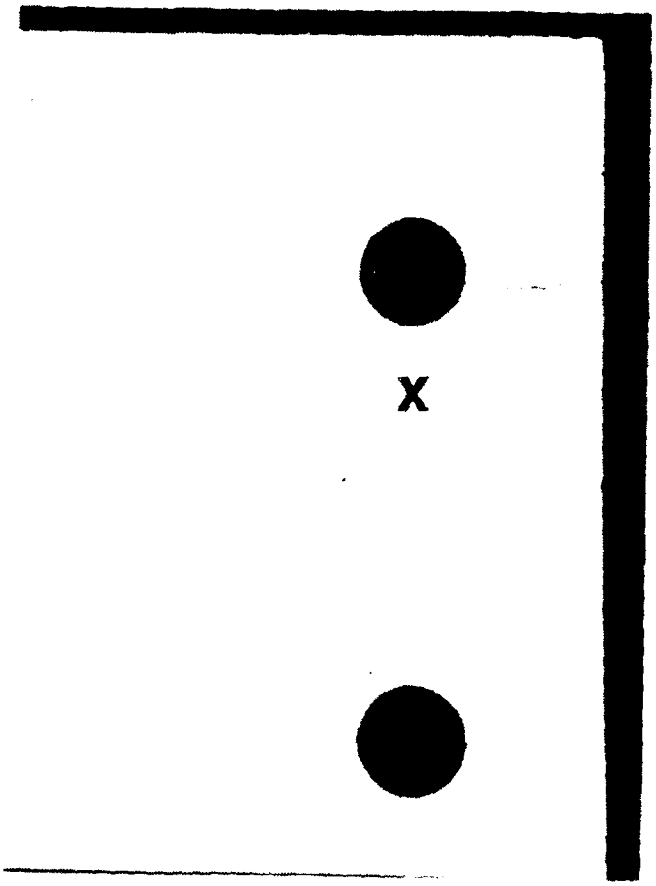


(d)

Mechanical Property Evaluation
- Tensile
- Charpy Impact
- Hardness

Durability Analysis

PART AND MATERIAL IDENTIFICATION

The three aluminum trunnion castings had been coated with green paint and labeled part numbers 80063-A3020139-00X (X's are numbers associated with individual parts). They had been removed from antennas in service. These trunnions were cast at the U.S. Reduction Company, Munster, Indiana. The original cast material was 771.0 Al alloy but was later changed to ductile iron to sustain a torque up to 40 ft-lbs. The aluminum alloys studied in this report were represented by two different numerical codes: 771.0 and 771.2. They belong to the same family; 771.0 usually refers to sand castings and 771.2 refers to ingots. The 771.2 has a similar chemical composition as that of 771.0 except less Si (0.10 versus 0.15%) and Fe (0.10 versus 0.15%) are specified. [1] Because these cast aluminum alloys are not weldable, [2] parts made of these alloys are usually joined by mechanical means. These QRSA trunnion castings are connected to the base with bolts. Any externally applied mechanical stress overloads at the joints might result in cracks. The 771.0 Al alloy under T6 temper condition also has only marginal resistance to general corrosion and to stress-corrosion cracking. [3]

Ductile iron is a cast iron with all or most of its second phase graphitic carbon in the form of spheroids or nodules; this results from the addition of alloying elements, such as magnesium to the liquid melt. It is also known as spheroidal or nodular iron. The as-cast microstructure normally consists of graphite nodules surrounded by ferrite (bull's-eye structure) in a matrix of pearlite; it may also include some free cementite. [4] As specified by ASTM, the ductile iron of grade 100-70-03 has minimum ultimate tensile and yield strengths about 690 and 483 (100 and 70 ksi), respectively, and a minimum ductility value of 3%. [5]

The composition and properties of these materials are summarized in Table 1. The reference values of properties were quoted from ASM and ASTM Handbooks. [5 and 6] The analyzed compositions were quoted from an earlier report [7] for 771.0 aluminum alloy and provided by North Manchester Foundry, Inc. (NMF), North Manchester, Indiana [8] for the ductile iron. Both typical and minimum values of mechanical property for 771.0 Al alloy are listed. They were determined using separately sand cast bars with a 1/2-in. diameter. The effects of casting section thickness on properties were not considered. The minimum property values listed in Table I should not be interpreted as the conventional "minimum or limit values" used in mechanical design practices. However, this data serves as a useful reference for relative property comparison and quality control. 771.0 Al alloy is in a T6 condition and the ductile iron (grade 100-70-03) is in a tempered condition.

MICROSTRUCTURAL ANALYSIS

Metallographic Examination

Metallographic studies by NMEL concluded that incipient melting was beginning to occur during the solution treatment of the Al castings. [7] Long and narrow secondary constituents, some having sickle or crescent shapes, were found at grain boundaries and the triple points of grain boundary intersections. These secondary phases were evidence of accidental heating above the eutectic temperature during the solution treatment. The poor temperature control was

Table 1. Materials characteristics [Ref. 5-8]

Property/Composition	771.0 Aluminum Alloy - T6		Ductile Iron (Tempered) Grade 100-70-03
Nominal Composition (%)	6.5-7.5 Zn, 0.8-1.0 Mg, 0.10-0.20 Ti, 0.06-0.20 Cr, 0.15 max Si, 0.15 max Fe, 0.10 max Cu, 0.10 max Mn, rem Al		N/A
Analyzed Composition (%)	6.7% Zn, 0.85% Mg, 0.18% Ti, 0.07% Cr, <0.04% Si, <0.02% Fe, 0.05% Cu, <0.03% Mn, rem Al		3.64 C, 2.59 Si, 0.62 Mn, 0.379 Cu, 0.134 Mo, 0.073 Cr, 0.051 Mg, 0.035 Ni, 0.011 S
	Typical	Minimum	Minimum
Ultimate Tensile Strength, MPa (ksi)	345 (50)	290 (42)	690 (100)
Yield Strength MPa (ksi)	275 (40)	241 (35)	483 (70)
Elongation (%)	9.0	5.0	3.0
Hardness (Brinell)	N/A	90	N/A
Density $lb/in^3(g/cm^3)$	N/A	0.102 (2.823)	N/A

consequently cited as a possible cause for the failure of Al trunnion castings. For comparison and confirmation of this conclusion, NMEL attempted to obtain some as-cast materials and heat-treated (T6) specimens from the manufacturer and developer of the Al casting alloy Precedent 71 (AA771), U.S. Reduction Company. Aluminum casting alloy Precedent 71 was the former name before the alloy was officially designated as 771.2 Al alloy. Neither the reference micrographs or the as-cast ingots were ever sent to NMEL. However, in November, 1990, U.S. Reduction Company furnished ARL-Watertown with one as-cast 771.2 Al casting for metallographic analysis. Extensive metallographic studies at ARL-Watertown showed that the as-cast and the heat-treated specimens had very similar microstructures. The structure of the heat-treated sample showed equiaxed grains with both angular and spherical cavities, and secondary constituents along the grain boundaries as shown in Figure 3. Since a similar microstructure of porosity and secondary constituents also existed in the as-cast sample before solution treatment, as shown in Figure 4, we concluded that these features resulted from the casting/solidification process rather than by the subsequent solution treatment. Any rounded cavities and secondary constituents were isolated and usually randomly distributed in the matrix and along the grain boundaries; the sickle- or crescent-shaped ones were often in clusters or networks along the grain boundaries, particularly at the grain boundary triple intersection points. We observed more dendritic cells in the as-cast material, but the size and volume fraction of porosity and secondary constituents were about the same in the heat-treated and the as-cast samples. No evidence indicated that cracks initiated at these cavities, secondary constituents or the grain boundary triple points. It was our conclusion that incipient melting did not occur during the solution treatment and was not the major cause for failure.

Figure 5 shows the nodular microstructure of the ductile iron casting that replaced the Al cast alloy. It has a typical bull's-eye structure with graphite nodules surrounded by ferrite in a pearlite matrix. The existence of any excessive amount of free carbide in ductile iron would impair its ductility and machinability. Since only a few scattered free carbide particles were observed in

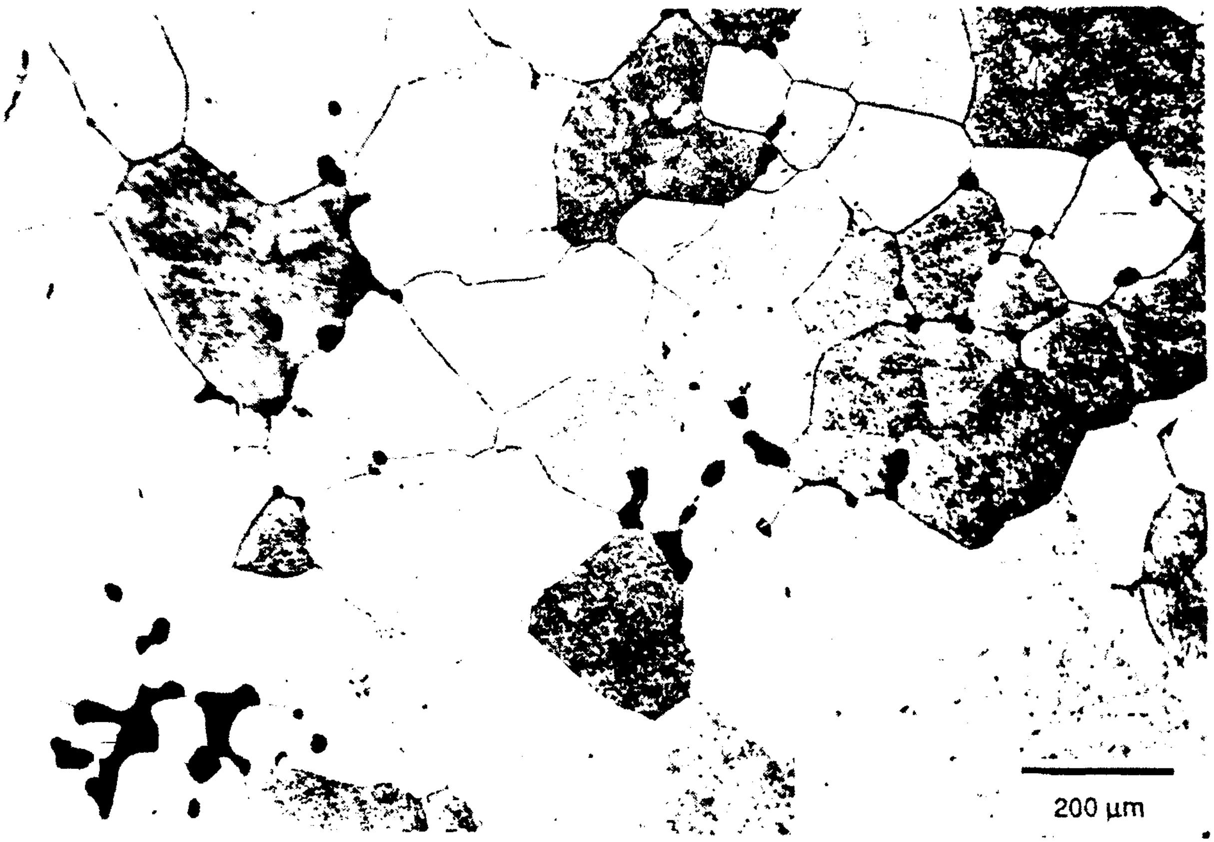
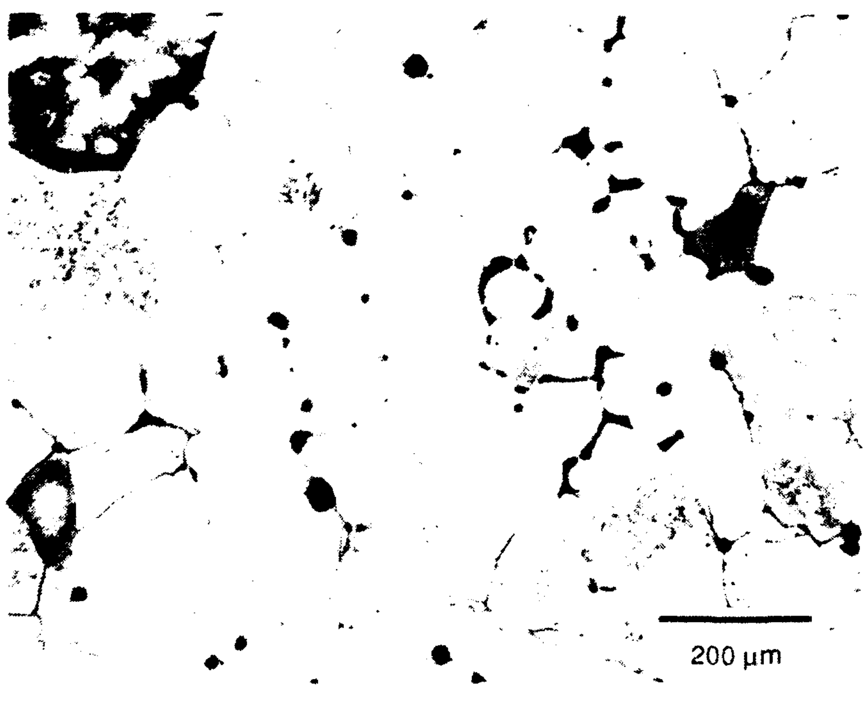


Figure 3. Equiaxed microstructure of a heat-treated 771.0 Al sample showing both angular and spherical cavities and secondary constitutents.

Figure 4. Microstructure of as-cast 771.2 sample which is similar to that of heat-treated material as shown in Figure 3.



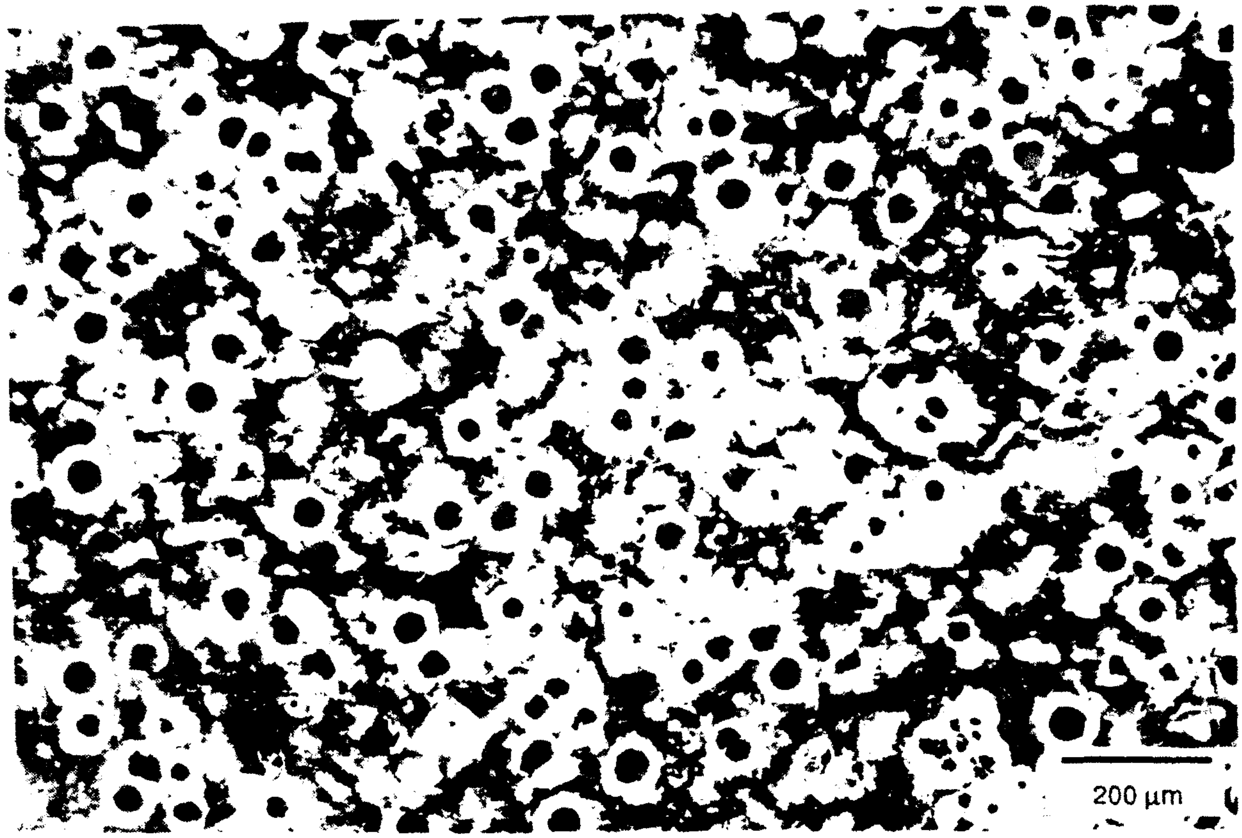


Figure 5. The nodular microstructure of the ductile iron showing graphite nodules surrounded by ferrite in a pearlite matrix.

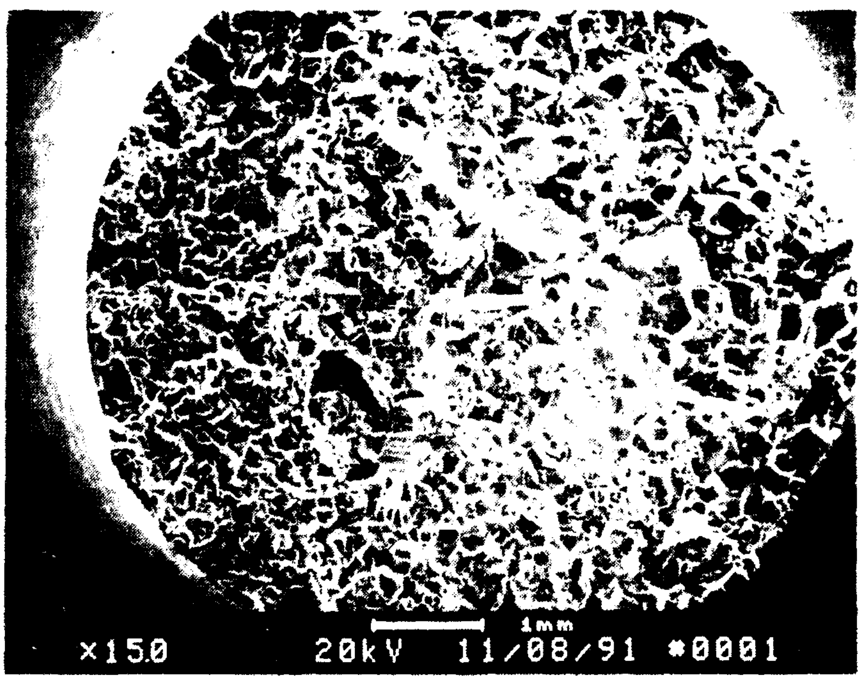


Figure 6. An overall tensile fracture surface of the Al trunnion casting sample indicating brittle fracture with secondary cracks.

the sample material and a higher-than-specified elongation was obtained for this ductile iron (see later section - Mechanical Property Evaluation), their effects were rather insignificant. All bull's-eyes are about the same size and are evenly distributed in the matrix. As expected, there was no debonding or cracking between the boundaries of the graphite/ferrite or ferrite/pearlite. The presence of microporosity and carbides was also minimal. In summary, our examination found that the vendor produced a sound ductile iron casting.

SEM Fractographic Study

NMEL found similar fracture surface appearances and topography (blocky or rock-candy type) for both samples that had been in service and those produced in the laboratory by overload. The blocky or rock-candy type fracture was evidence that the fracture mechanism was exclusively intergranular. Several inclusions and voids were observed in the casting, but no shrinkage porosity was discerned on the fracture surfaces of the pre-existing cracks. It was concluded that in-service failures were induced by overloads based on the similarity with fracture surfaces of tensile bars pulled to failure. [7] A SEM fractographic study at ARL-Watertown arrived at similar conclusions. Figure 6 shows an overall fracture surface of the 771.0 Al trunnion casting tensile specimen indicating brittle fracture with secondary cracks. The sickle-shaped voids were clearly revealed at higher magnification in Figure 7. Intergranular fracture with rocky facets is illustrated in Figure 8. Residual dendritic cells and river-pattern fracture were also observed as shown in Figure 9. In a brittle coarse-grained material cracks usually propagate along the weakest crystalline planes or along the grain boundaries. As a result, a combination of cleavage brittle fracture with river patterns and intergranular fracture occurred in the cast 771.0 Al trunnion.

The tensile specimen of ductile iron tested at room temperature showed little or no necking and the fracture surface was flat. Any secondary (either longitudinal or transverse) cracks on the external specimen surface immediately underneath the fractured cross-sectional surface were also minimal. The overall tensile fracture fractograph of ductile iron is shown in Figure 10 indicating a brittle fracture. Minor secondary cracks were observed in the matrix of the fracture surface, however the interfaces between the nodular graphite and the matrix were mostly intact without interfacial debonding as shown in Figure 11 and in the back-scattered SEM photo of Figure 12. Closer examination showed fractured pearlite lamellae indicating that the transgranular cleavage mechanism predominated in the matrix as shown in Figure 13. Cracks were also observed in a graphite nodule in Figure 13. Many graphite nodules were left intact as spheroids but several others were sheared during crack propagation. Only limited stretching elongation was observed around most graphite nodule-bearing cavities due to the low ductility. However, most graphite nodules remained in place after fracture. Some cracks interconnecting adjacent graphite nodules were observed but not too frequently. In summary, there were three major operative fracture modes: first, brittle cleavage fracture with river pattern and plateau characteristics predominated in the pearlitic matrix; second, brittle fracture was observed around isolated graphite nodules because the surrounding ferrite rings were under severe mechanical restraint due to the harder and nondeformable pearlitic matrix; finally, relatively ductile tearing and microvoid coalescence occurred in areas clustered with closely-spaced graphite nodules and mild cup-cone type fracture was also observed.

Figure 7. Sickle-shaped intergranular cavities in the Al trunnion casting.

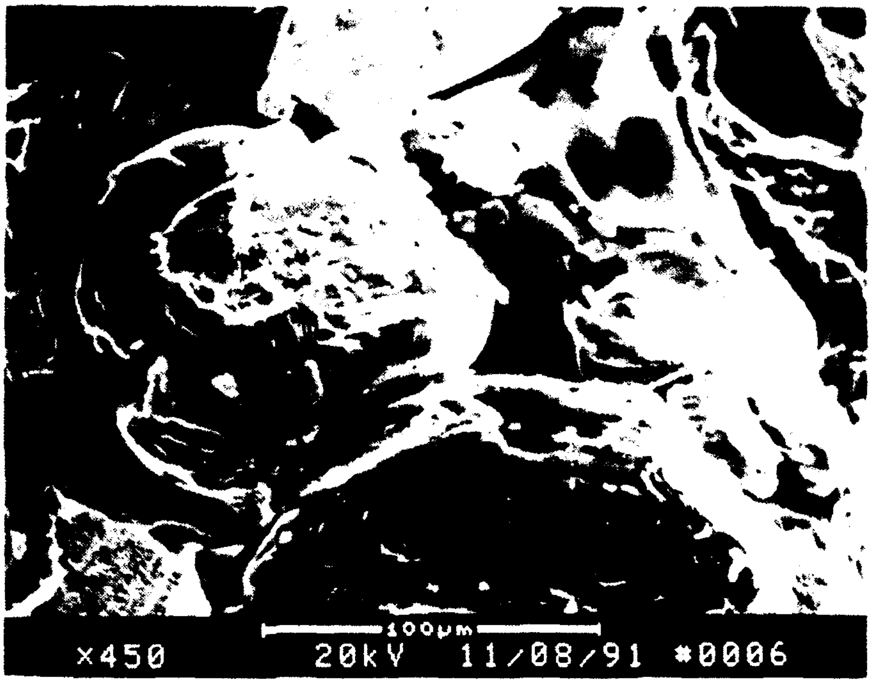


Figure 8. Intergranular rocky fracture observed in the Al trunnion casting.

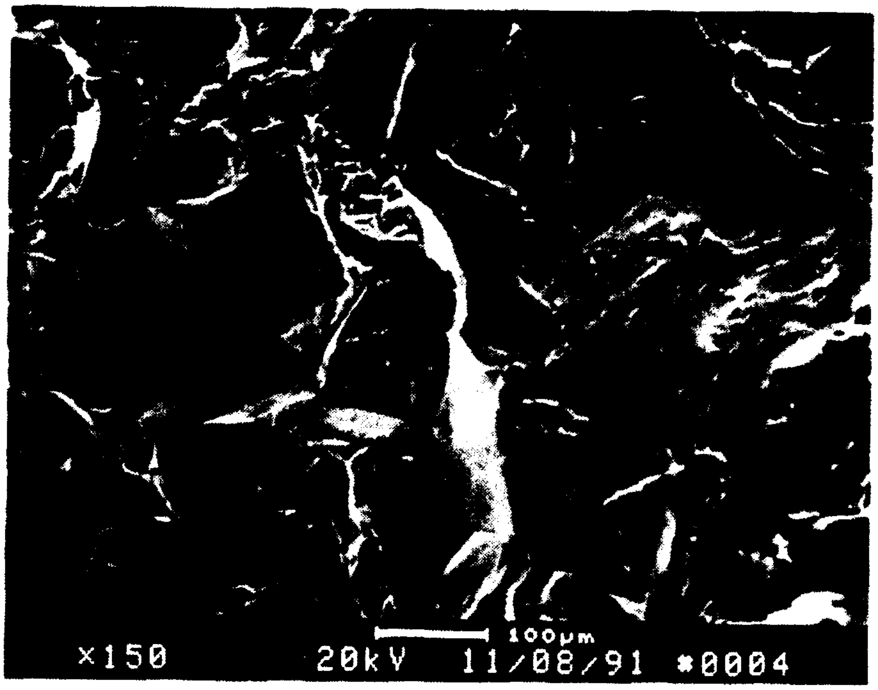


Figure 9. Residual dendritic cells and river pattern fracture observed in the Al trunnion casting.

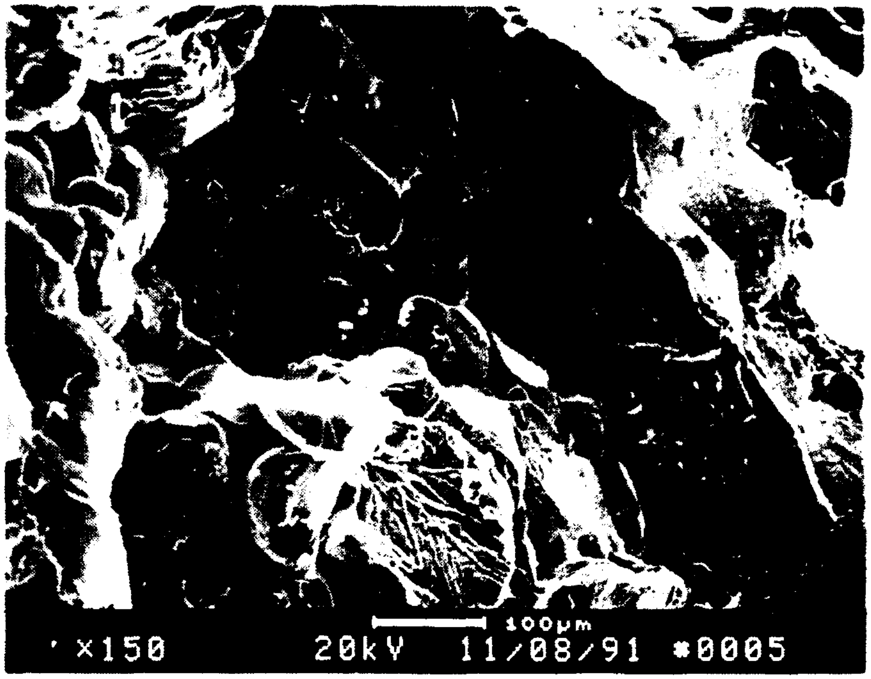


Figure 10. SEM fractograph of the ductile iron tensile specimen.

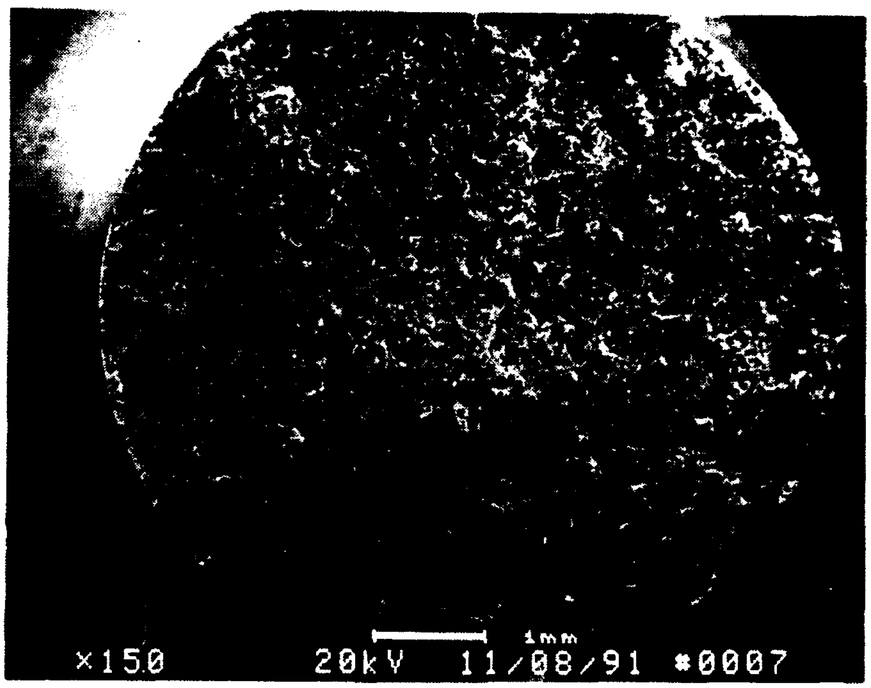


Figure 11. SEM fractograph of the ductile iron tensile specimen showing minor secondary cracks in the matrix.

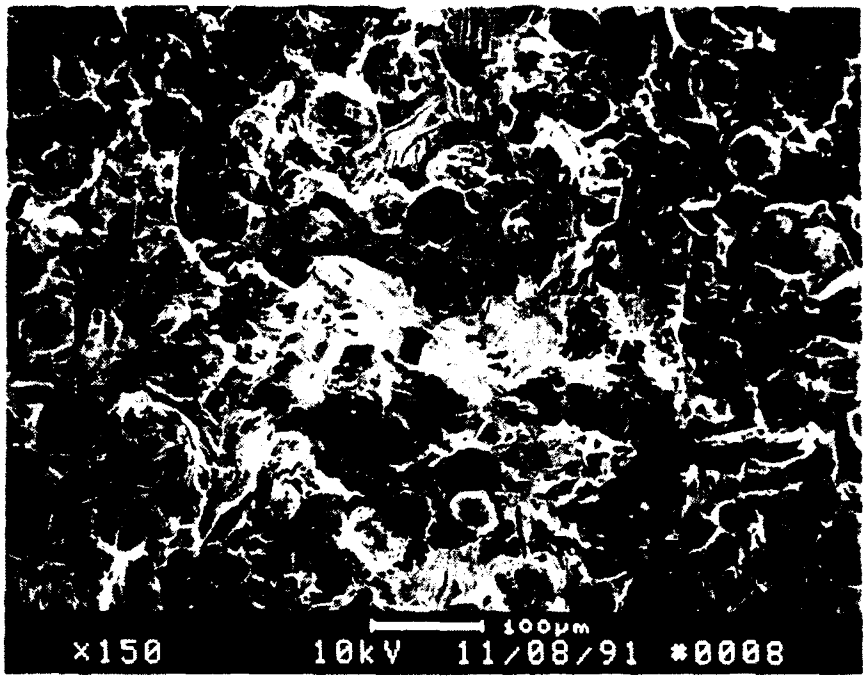


Figure 12. Backscattered SEM fractograph of the ductile iron tensile specimen.

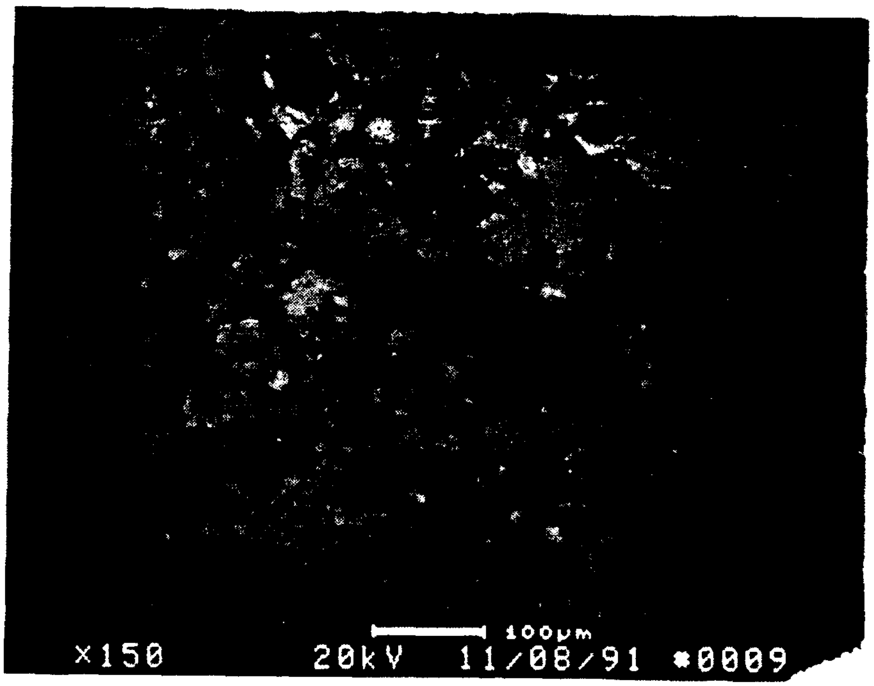
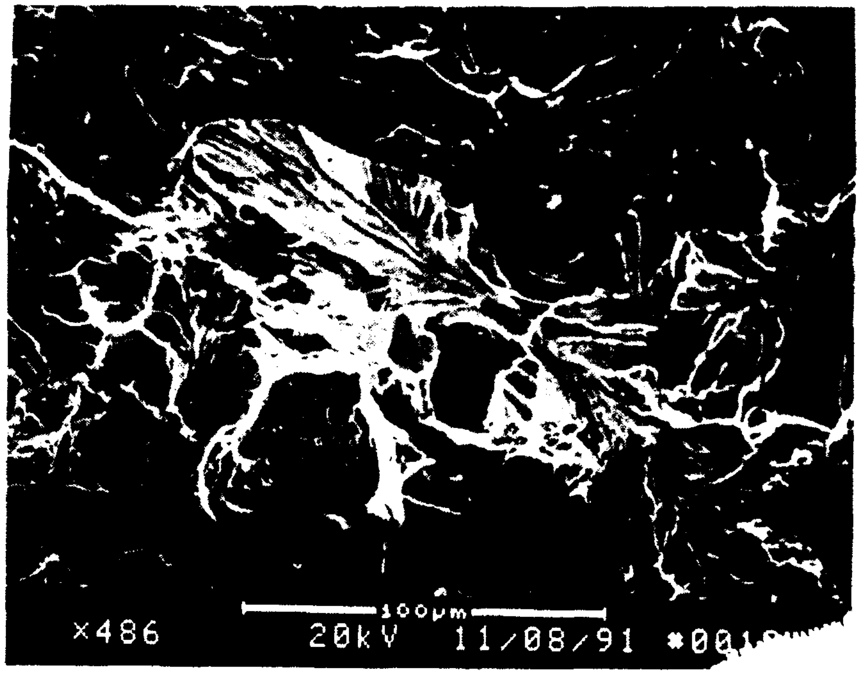


Figure 13. A higher magnification fractograph of the ductile iron tensile specimen showing transgranular cleavage fracture in pearlite.



CRACK DETECTION AND RADIOGRAPHIC ANALYSIS

The previous investigation [7] reported that when Al QRSA trunnion castings in service at Shaw AFB were stripped of paint, liquid penetrant inspection revealed cracks in these castings. Some of the larger cracks were visible with the naked eye and open porosity of 1/8 inch in diameter was reported. These findings were later confirmed by NMEL and more cracks were also identified in the same castings by eddy current inspection.

Extensive radiographic inspection was conducted on a ductile iron casting at ARL-Watertown. In contrast to the aluminum castings reported in the previous investigation, neither hair-line cracks around the bolt holes nor larger cavities were observed in the ductile iron casting. As indicated in Figure 14 only minor shrinkage (points A, B, and C) and porosity (points D, E, and F) existed. These "defects" were considered within the frame for regular castings. The relative contrast thickness ratios at points 1, 2, and 3 were 2.05 : 2.41 : 3.07. From the radiographic analysis it was concluded that there was no unusual inherent defect in the ductile iron trunnion resulting from the casting process.

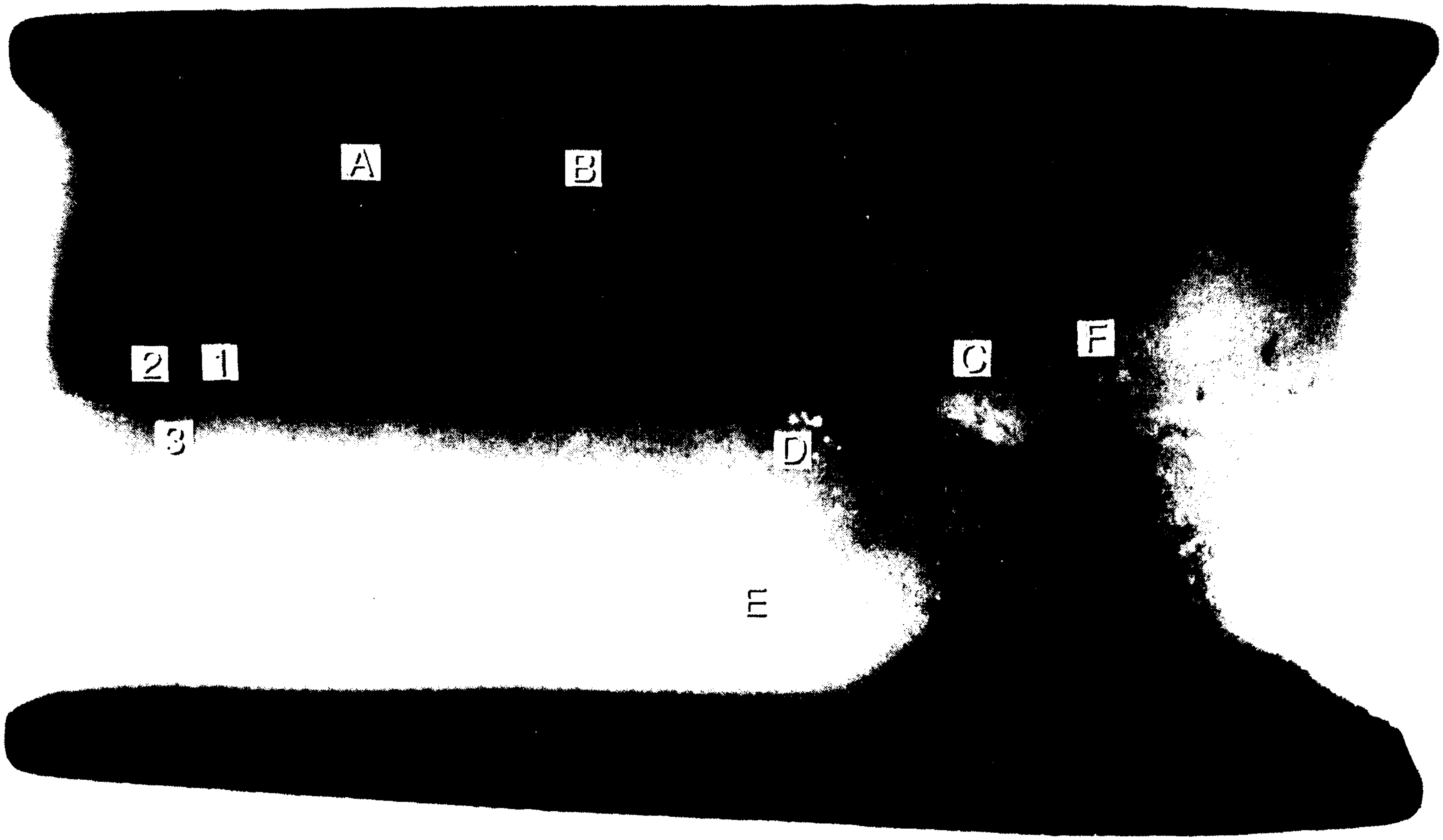
MECHANICAL PROPERTY EVALUATION

Compared with the minimum values of properties listed in Table 1, the ARL-Watertown test results for Al castings, in Table 2, are slightly higher for ultimate and yield tensile strengths; a lower ultimate tensile strength was reported by NMEL. Note however, that a much lower elongation was measured for these castings, by at least a factor of 2 less than the specified values. According to the Federal Specification for Aluminum Alloy Sand Castings, QQ-A-601F, Section 3.3.2.1, "Unless otherwise specified, the average ultimate tensile strength and average elongation of test specimens cut from castings ..... shall be no less than 75 percent and 25 percent, respectively, of the values specified (in Table 1) for separately cast bars." Thus, in general these Al castings have passed the specification requirements for mechanical properties.

The cast iron mechanical property values reported by ARL-Watertown and NMF are comparable with the reference values in Table 1. The only significant difference is the higher elongation, 9.3 (or 10)% versus 3%, which is considerably above the requirement. The good elongation values are consistent with the yield strengths that are close to the required minimums.

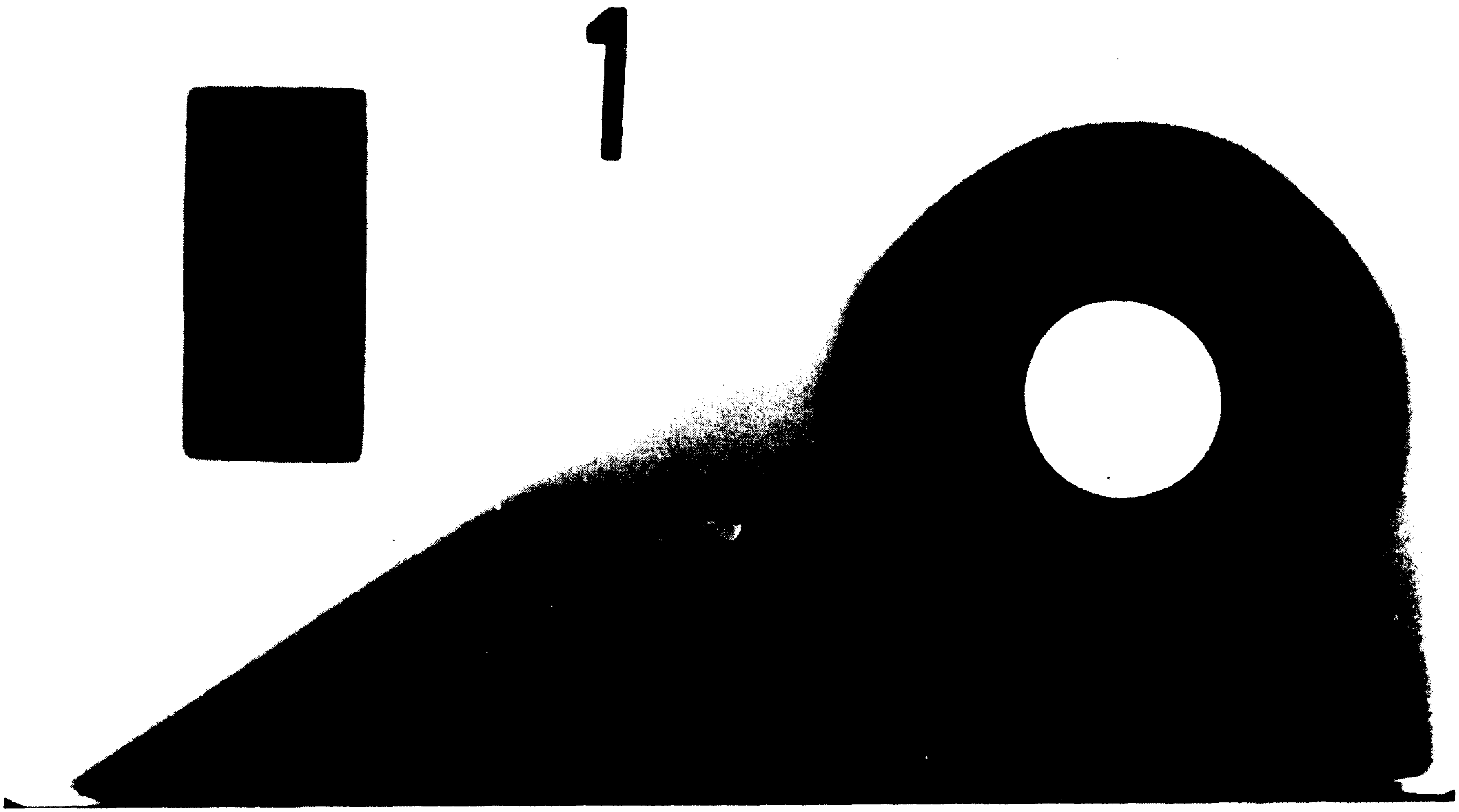
Table 2. Measured materials properties

Property	771.0 Al Alloy		Ductile Iron Grade 100-70-03	
Source	ARL-Watertown	NMEL (7)	ARL-Watertown	NMF (8)
Ultimate Tensile Strength, MPa (ksi)	299 (43.3)	272 (39.4)	746 (108.2)	730 (105.9)
Yield Strength MPa (ksi)	285 (41.4)	N/A	441 (64.0)	474 (68.7)
Elongation (%)	~2	2.5	9.3	10.0
Reduction of Area (%)	<2	N/A	6.3	N/A
Charpy Impact (ft-lb)	N/A	N/A	2.67	N/A
Hardness (Brinell, Rockwell B or C)	N/A	55.1~59.3 (Rockwell B)	19.9 (Rockwell C)	241 (Brinell) 22~23 (Rockwell C)



(a)

Figure 14a. Radiographic analysis of the ductile iron casting: shrinkage at A, B, and C and porosity at D, E, and F. Relative contrast thickness 1:2:3 = 2.05:2.41:3.07. (a) top view,



(b)

Figure 14b. Radiographic analysis of the ductile iron casting (b) right side view,

(c)

Figure 14c. Radiographic analysis of the ductile iron casting (c) left side view.

The tensile properties reported by ARL-Watertown are the average of 4 tests for Al casting and 3 for ductile iron, respectively. The Charpy impact value is the average of 6 tests and the hardness value is the average of 28 tests. The tensile data from NMEL is the average of 7 tests.

DURABILITY ASSESSMENT

The trunnion casting is subject to dynamic loading in service and the exact stress cycles are not available. Arguments have been made on the various causes of repeated failures. The 771.0 Al alloy was originally chosen for its lightweight. Despite disagreement on the causes of failure, the repeated failures demonstrate that its mechanical strength at best only provides a low margin of safety in service.

A crack was even found in a spare Al casting before it was put into service. As indicated in the earlier Naval report, a fine, circumferentially oriented crack was observed immediately adjacent to a bolt hole in a cast Al trunnion which was sent for comparison to NMEL from the stock of spares at Harris Corporation. [7] This is indicative of poor quality control of the casting process.

The contractor, Harris Corp., has installed about 189 sets of QRSA in the field. Each set contains two trunnion castings. As of November 25, 1991, about 60% QRSA have replacement ductile iron trunnion castings and the rest are expected to be replaced in the following six months. The substitution of ductile iron (grade 100-70-03) for 771.0 Al provides a much larger strength safety margin but with a heavy weight penalty. No failures have been reported since this change of cast material started about one year ago (as of November 25, 1991). The durability of the new cast trunnion with ductile iron has been significantly improved.

DISCUSSION AND CONCLUSIONS

Based on the available information at that time, the conclusions in an earlier Naval report [6] included the following findings:

1. The material of the QRSA trunnion Al castings met all of the requirements of Federal Specification, QQ-A-601(F).
2. Microvoids with characteristics of both incipient melting and gas porosity were observed, however, their location and irregular shapes suggested incipient melting. The presence of crescent-shaped secondary constituents on the grain boundaries and grain boundary intersections also suggested incipient melting.

After more reference material was made available for evaluation the current study agreed with item 1 but concluded differently for item 2. NMEL did not receive the as-cast ingot at the time it issued the report on February 23, 1990. Thus, a direct comparison of metallographic features between the as-cast and the heat-treated (T6) specimens was not made. Based on their limited observations the beginning of incipient melting was strongly suggested. However, it was reported that there was not sufficient evidence to firmly support or exclude either of the two mechanisms, gas entrapment or incipient melting, for forming the microvoids.

Incipient melting may occur at grain boundaries during solution treatment by heating the specimen above the local liquidus temperature. The resulting microstructural characteristics are irregular microvoids on grain boundaries and grain boundary intersections, and a lacy network of grain boundary secondary constituents; but these are not sufficient conditions for proof of the occurrence of incipient melting. All these features were observed by NMEL and ARL-Watertown for the heat-treated specimens, and a very similar microstructure was also observed for the as-cast ingot reference sample at ARL-Watertown. In particular, about the same amount of microvoids and secondary grain boundary constituents were found in both as-cast and heat-treated samples. It is concluded in this study that the microvoids and secondary constituents formed during the process of casting and not as a consequence of incipient melting during the subsequent solution treatment.

Finally, the substitution of the aluminium trunnion casting with ductile cast iron has solved the original cracking problem and greatly improved service reliability.

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REFERENCES

1. Registration Record of Aluminum Association Alloy Designations and Chemical Composition Limits for Aluminum Alloys in the Form of Castings and Ingot, pp.1-11, the Aluminum Association, Inc., Washington, D.C., 1989.
2. ASM Metals Handbook, v.2, 9th ed., Metals Park, Ohio, 1979, p.193.
3. ASM Metals Handbook, v.2, 9th ed., Metals Park, Ohio, 1979, p.210.
4. ASM Metals Handbook, v.9, 9th ed., Metallography and Microstructures, Metals Park, Ohio, 1985, p.245.
5. Annual ASTM Book of Standards, A536-84, v.1.02, "Standard Specification for Ductile Iron Castings," Philadelphia, PA, 1990, p.303.
6. ASM Metals Handbook, v.2, 9th ed., Metals Park, Ohio, 1979, p.178 and p.149.
7. F.W. Johnston, Materials Engineering Laboratory Report No. 341-3-90, QRSA Trunnion Casting #139 Failure Analysis, Naval Aviation Depot, Naval Air Station, Jacksonville, Florida, Feb., 1990.
8. Private communication with North Manchester Foundry, Inc., North Manchester, Indiana.

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